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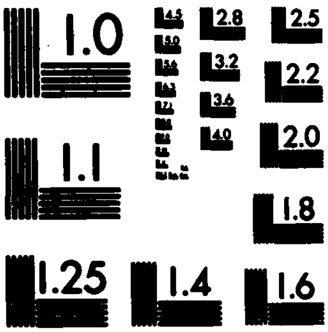

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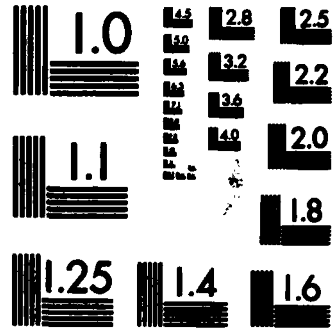

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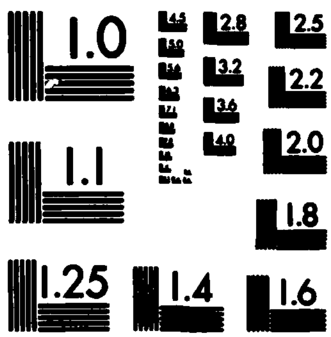

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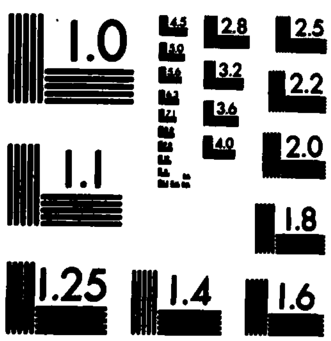

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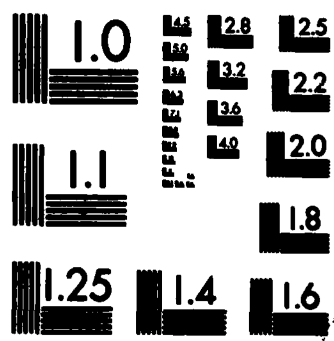

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NPRDC TN 81-20 JULY 1981

DESIGN ENGINEERS' CONCEPTS OF SKILLS FOR SYSTEM OPERATION AND MAINTENANCE

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NPRDC Technical Note 81-20 July 1981

DESIGN ENGINEERS' CONCEPTS OF SKILLS FOR SYSTEM OPERATION AND MAINTENANCE

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FOREWORD

This development was conducted in support of Navy Decision Coordinating Paper, Z0109-PN under subproject Z0109-PN.03 (Manpower Cost in System Design) and was sponsored by the Deputy Chief of Naval Operations (OP-01). The subproject concerns the application of human engineering technology in the development of procedures to incorporate hardware/software/personnel trade-offs and cost benefit alternatives in all stages of system design.

The present development was undertaken in 1978 to gain insight into how engineers conceptualize skills required of personnel who operate and maintain the hardware systems being designed for future Navy use. Information obtained was used to prepare a draft version of an engineer's guide entitled Designing for Human Skills in Navy Electronic Systems (NPRDC TN 81-15). Further development of this guide was abandoned in favor of a related guide published as An Engineer's Guide to the Use of Human Resources in Electronic Systems Design (NPRDC TN 79-8) and an evaluation of that guide (NPRDC SR 81-3). Information obtained through the earlier engineers' concepts effort is being documented at this time for distribution to the research community.

The contracting officer's technical representative was Mr. Ernest A. Koehler.

JAMES F. KELLY, JR.
Commanding Officer

JA... ?. REGAN
Te... Director

SUMMARY

Problem

In the design process for new hardware, selection of a particular configuration influences such factors as the number, skills, and training needs of operating and maintenance personnel required to support the system. These, in turn, significantly influence manpower life cycle costs. Despite the importance of these equipment-personnel trade-offs, in which skill is a primary factor, the hardware developer often has little understanding of the impact his decisions will have on personnel factors.

Objectives

This effort was conducted as part of a program aimed at developing tools for the hardware developers to use in assessing the personnel implications and costs of alternative design options.

The objectives of this effort were to determine (1) the kinds of skill concepts engineers apply to their designs and (2) whether the sophistication of these skill concepts can be increased by presenting the engineer with a structured framework based on behavioral research.

Approach

A battery of tests was developed and administered to a representative group of 40 design engineers. The procedure required engineers to estimate skill levels required by operation and maintenance tasks. In an <u>unstructured</u> survey, the engineers were asked to list the most important tasks to be performed in the operation or maintenance of equipment on which they had recent design experience. For each combination of any three tasks listed, the engineers were asked to indicate the name of the skill required by any two of these tasks and the degree of skill required by each.

In a <u>structured</u> survey, the engineers were given two sets of cards. One set included 29 cards, 15 of which described an operation task, and the other 14, a maintenance task.

The other set included 22 cards, 11 of which described a cognitive skill, and the other 11, a psychomotor skill. For each of these skills, engineers were to sort the task description cards into five skill levels; that is, they had to determine whether the task required none, a small amount, a moderate amount, a high degree, or a maximum amount of the skill in question.

Conclusions

1. Engineers have relatively few and nondifferentiated concepts of operation and maintenance skills.

2. They consider that the skills required for operating and maintenance tasks differ significantly. Equipment maintenance is more difficult, requiring a higher level of skill that is oriented primarily on cognitive capabilities, whereas operating tasks require only psychomotor abilities.

3. It is possible to increase the sophistication of the engineers' skill concepts by providing them with a structured situation that leads them through the skill-analysis process.

Recommendation

A personnel design requirements handbook should be developed to enable design engineers to assess the personnel implications of hardware system design concepts.

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INTRODUCTION

Problem and Background

This development is part of an effort to optimize the manpower required to operate and maintain Navy systems. Personnel costs are the major part of life cycle costs. For example, personnel costs represent about 61 percent of the total FY78 DoD budget (King, 1977), and personnel costs account for about 58 percent of the annual operating expense for each DD 963 class destroyer (Director of Defense Research and Engineering, 1973).

The higher the skill level demanded by Navy equipment, the more costly the personnel who must operate and maintain that equipment. This is because these skills must be provided by personnel who have completed Navy training, and the greater the skill demanded, the longer and more expensive the courses required to train those skills. Therefore, a primary requirement in attempting to reduce manpower costs is to reduce the skills needed to utilize Navy equipment.

It is obvious that the design of Navy equipment determines manning in general, and personnel skill level in particular. Taylor (1975) indicated that 70 percent of the life cycle costs of new systems are determined by decisions made in the concept phase of hardware development. If manpower needs and their associated costs are to be reduced, the nature of equipment design must be influenced early, so that fewer skilled personnel are required.

Is this possible? Although technological advances and increased technological sophistication work against this, the fact remains that alternative equipment designs are possible for any system requirement. In other words, to satisfy the same requirement one can, for example, design systems that are completely automated, partially automated, or largely manual. Some of these designs demand personnel with lower skill levels than others. All other things being equal, if the designers are aware of two alternative designs--one demanding a lower skill level than another--they are more likely (or at least it is a logical expectation) to select the alternative calling for fewer personnel with lower

skills. This is the thinking represented by contract specifications calling for the simplest possible design tailored to the lowest possible skill levels.

Design engineers are at the center of efforts to reduce manpower, because they are largely responsible for the equipment configuration that ultimately reaches the Navy. It is, therefore, necessary to determine whether engineers are aware of skill factors and their relationships to design characteristics. If it is difficult for them to differentiate between alternative configurations on the basis of the required skills, they cannot make design trade-offs involving skills and select the most cost-efficient design alternative.

It is essential to investigate the engineers' "conceptual space" so that means can be found of influencing their design perceptions. Unfortunately, relatively little is known about engineers despite their central role in system development. Previous studies (Meister, Sullivan, & Askren, 1968; Askren & Lintz, 1975) have demonstrated the feasibility of studying the engineer as an element in design, but much more remains to be learned.

Objectives

This study was conducted as part of a program aimed at developing tools for the hardware developers to use in assessing the personnel implications and costs of alternative design options.

The objectives of this effort were to determine (1) the kinds of skill concepts engineers apply to their designs and (2) whether the sophistication of these skill concepts can be increased by presenting the engineer with a structured framework based on behavioral research.

METHOD

Subjects

In any study in which the design process is at issue, the selection of the subject sample is extremely important. Unfortunately precise criteria for differentiating between different types of engineers [illegible]. At the very least, however, one should

be concerned with: (1) level of design experience (system or major assembly), (2) knowledge of operation or maintenance functions, and (3) type of system or major assembly designed.

Table 1 shows the characteristics of the subject engineers. Thirty-two subjects were selected from Hughes Aircraft Corporation and eight from the Autonetics Division of Rockwell International.

Table 1

Characteristics of the Subject Sample

Type of System	Operation Tasks		Maintenance Tasks	
	System Level	Major Assembly Level	System Level	Major Assembly Level
Command/control	2	2	2	2
Communications	2	2	2	2
Fire control	2	2	2	2
Surveillance	2	2	2	2
Autonetics	2	2	2	2

Subjects' ages ranged from 24 to 57 years, with a median of 43 years. Their design experience ranged from 1 to 36 years, with a median of 15 years. The percentage of years in a supervisory role ranged from 0 to 100 percent, with a median of 10 percent.

The distribution of education, as indicated by the highest year of formal schooling completed, is shown in Table 2.

The major subject areas of academic training reported (at some time during formal education program) included business administration (1), computer science (4), economics (1), electronics (4), engineering (3), electrical engineering (19), mechanical engineering (2), systems engineering (2), general science (2), management (1), mathematics (4), physics (5), and psychology (1). The total number exceeds 40 because several persons worked in different major subject areas during undergraduate school than in graduate school.

Table 2

Distribution of Subject Education

Highest Year	No. of Subjects
12	1
13	2
14	4
15	1
16	12 (median)
17	8
18	9
19	2
20	1

Recent design experience was reported on these Navy electronic systems: Surface Towed Array Sonar System, Surface Sonar System Modernization Program, Improved Point Defense Target Acquisition System, Electro-Static Gyro Monitor, AN/UYQ-21 Computer Display Set, Navy Tactical Data System, Position Locating and Reporting System, DD 963 Electronics System, DD 963 Exterior Communications System, Secure Voice System, Anti-Ship Torpedo Defense System, AN/SPS-52 Radar System, AN/PRC-104 Radio, JTIDS/TDMA "B" Terminals, CV-TSC (ASW Sonar), Tunable Attributes System, Fast-Time Analyzer System, Shipboard Data Multiplex System, Aided Display Submarine Control System, and Passive Sonar Processing System.

Motivation was excellent in all cases, except for two subjects who were judged to be neutral. The most frequent comment was that most system design efforts did not remotely approach the level of detail on task and skill requirements evident in the test battery. Several supervisory engineers requested copies of the task and skills lists to use in checklist fashion in future proposals or system designs.

Test Procedure

The procedure employed required engineers to estimate skill levels required by operation or maintenance tasks which they generated.

In the unstructured survey, the engineers were asked to assume that they were currently involved in the design of equipment on which they had recently worked. (The instruments used are presented in the appendix.) The following steps were performed for operation and maintenance tasks:

1. They were asked to list the most important tasks to be performed for operation or maintenance of that equipment.

2. For selected combinations of the tasks listed in step 1, taken three at a time, they were asked to indicate (in their own words) the skill required by any two of these tasks.

3. Having now specified the skills required by these tasks, the subjects were asked to indicate the degree of that skill required by each of the tasks listed in step 1.

In the structured survey (the instructions are in the appendix), the following steps were performed:

1. The subjects were given a set of 29 cards, one for each of the 15 operation task descriptions and the 14 maintenance task descriptions (shown in Table 3). These task descriptions were developed after review of task taxonomies previously developed by Askren (1976); Berliner, Angell, and Shearer (1974); Finley, Obermayer, Bertone, Meister, and Muckler (1970); Parker (1975); and Wylie, Dick, and Mackie (1975).

2. The subjects were also given a set of 22 cards, one of each of 11 cognitive skills and 11 psychomotor skills. The skills taxonomy was based largely on the factor analytic research of Fleishman (1972), as modified by Ekstrom (1973) and, particularly, Dunnette (1976). The skills are also listed in Table 3.

Table 3

Task and Skill Descriptions

Title	Description
Task Descriptions	
Operation:	
1. Initiate equipment operation	Set up and initialize equipment/system in accordance with established procedures.
2. Establish desired operating modes	Select and set up specific operating modes in response to established criteria, or in response to changing operating conditions.
3. Perform correct sequence of operating procedures	Operate equipment/system in accordance with established procedures and the requirements of command and/or the environment.
4. Observe and interpret visual displays and indicators	Scan, detect, identify, extract features of, and process the absence or presence of in-tolerance or out-of-tolerance data presented via equipment/system visual displays and indicators.
5. Recognize and interpret auditory signals	Detect, identify, extract features of, and process the absence or presence of in-tolerance or out-of-tolerance conditions indicated by auditory signals.
6. Read and understand text	Read, interpret, and extract information from textual material (e.g., written, printed, or displayed).
7. Operate discrete control devices	Select and make correct use of discrete controls such as switches, selectors, and keyboards.
8. Operate continuous control devices	Select and make correct use of continuous control devices such as control sticks, trackballs, verniers, and wheels.
9. Interpret visual and auditory data to assist in decision making	Identify relevant visual and auditory signals, extract pertinent values, or data, and process them for use in making equipment/system operating decisions.
10. Perform quantitative computations	Using established logic and procedures and available tools, execute required computations utilizing quantitative information.
11. Select appropriate course of action	Based on available data, command instruction, precedent, and established procedures, determine a course of action matched to the mission and capabilities of the equipment/system.
12. Supply or enter data to implement decisions	Operate equipment/system devices to make data inputs that identify and implement the course of action selected.
13. Receive/transmit communications relevant to operation	Select appropriate mode of communication and receive or transmit data regarding equipment/system status, decisions, or future operation.
14. Monitor equipment operation	Locate, identify, and interpret equipment/system status indicators as required to ascertain that satisfactory operating conditions are being maintained.
15. Perform preventive maintenance	In accordance with established procedures, carry out the preventive actions required to maintain the equipment/system in satisfactory operating condition.
Maintenance:	
1. Obtain physical access to the equipment	Locate equipment requiring maintenance, approach it safely, and open/remove the necessary access panels.
2. Select and use tools necessary for maintenance	Recognize, acquire, and use correctly the tools appropriate to the maintenance tasks to be performed.
3. Perform preventive maintenance	Perform any and all tasks required on a periodic basis to maintain equipment in operational condition (e.g., cleaning, oiling, adjusting, removing, and replacing filters etc.).

Table 3 (Continued)

Title	Description
Task Descriptions	
Maintenance (Con t.):	
4. Operate BITE, and/or connect and operate support or test equipment	Select support or test equipment required for maintenance, connect/hook it up properly, and operate it correctly and safely.
5. Set initial conditions required for maintenance	Set up equipment/system in accordance with established maintenance/operation procedures.
6. Inspect equipment	Conduct a physical inspection of the equipment/system with regard to maintenance needs.
7. Isolate malfunction to identifiable unit	Using appropriate procedures, BITE, and/or test equipment and tools, locate or trace out-of-tolerance conditions or malfunctions to discrete or identifiable unit(s) or component(s).
8. Verify failure or malfunction	Using procedures, BITE, and/or test equipment and tools, verify the initial diagnosis as to the location and nature of the failure or malfunction.
9. Perform in-place adaptive corrections	If corrective action can be accomplished in-place, use procedures, tools and test equipment to do so.
10. Perform corrosion control procedures	Select and apply appropriate corrosion control action based upon equipment type, location, and status.
11. Remove malfunctioning unit/component	Isolate and physically remove defective unit/component from the equipment/system being served.
12. Replace malfunctioning unit/component	Acquire an operational unit/component and use appropriate procedures, tools, and test equipment to install it as a replacement for the malfunctioning unit/component.
13. Verify satisfactory functioning of replacement unit/component	Using established procedures, tools, and test equipment, verify that the replacement unit/component is functioning to specified tolerance levels.
14. Restore equipment/system to operational condition	Conduct necessary operating checks, remove all tools, test and support equipment, close up the equipment/system, clean up area, and return equipment/system control to operational personnel.
Skill Descriptions	
Cognitive:	
1. Pattern sensitivity	Ability to distinguish form or pattern within a confusing background, such as detecting a target or symbol in display clutter, or locating a particular object or tool in a box containing an assortment of such items.
2. Fluency	Ability to find ways of saying things that are most appropriate to particular situations, ideas, or concepts, such as summarizing developments in a tactical situation, or reporting and describing the nature of an unexpected malfunction.
3. Idea formation	Ability to find and test ideas that show how many things are interrelated within a larger system, such as making an assessment of a tactical situation, or summing up the nature of a system-level malfunction.
4. Rote memory	Ability to memorize related or apparently unrelated items and to recall most or all of the memorized information when presented with only an element or part of it, such as routine operational procedures, or diagnostic steps in fault isolation tasks.

Table 3 (Continued)

Title	Description
Skill Descriptions	
Cognitive (Con t.):	
5. Span memory	Ability to recall perfectly for immediate reproduction a series of items after only one presentation of the series, such as repeating flight data during air traffic control communications, or relaying sparepart nomenclature during urgent repair/replacement work.
6. Number facility	Ability to add, subtract, multiply, and divide rapidly with few errors, such as performing arithmetic operations involving date-time indications, display track headings, test instrument readings, or control settings.
7. Visual speed	Ability to detect visual signals quickly, make comparisons, and carry out other simple operations involving visual perception, such as detection of visual alert displays, or awareness of changes in equipment status indicators.
8. Deductive reasoning	Ability to reason from given data to the necessary conclusion, such as deciding on a course of action based on tactical displays and communications, or determining the nature of a malfunction based on indications during troubleshooting.
9. Spatial orientation	Ability to tell where subject is in relation to some object, or to tell where the object is in relation to subject, such as awareness of compass directions linking subject's location with the locations of related military units, or awareness of the location of particular equipments within a complex installation.
10. Spatial visualization	Ability to visualize forms and patterns in the imagination, and to move them about or change them mentally, such as ability to anticipate near-future tactical developments from present displays, or to see how to fit a component into an odd-shaped space.
11. Verbal comprehension	Knowledge of words and their meaning, as well as the application of this knowledge to the understanding of verbal communication, such as rapid and accurate understanding of operational orders and instructions, or technical manual passages and diagnostic task descriptions.
Psychomotor:	
1. Control precision	Ability to perform finely controlled muscular adjustments, such as moving a lever to a precise setting, or setting of vernier knob to an exact position.
2. Multilimb coordinating	Ability to coordinate the movements of arms and/or legs simultaneously, such as in climbing a ladder, operating a typewriter, or packing a number of equipment items into a box.
3. Response orientation	Ability to make correct and accurate movements in relation to a stimulus under highly speeded conditions, such as reaching out and flicking a switch when a warning horn sounds, or resetting the correct circuit breaker in a panel containing an array of circuit breakers.
4. Reaction time	Ability to respond rapidly when a stimulus occurs, such as answering an incoming telephone or radio call, or shutting down equipment when inoperable conditions are indicated.
5. Speed of arm movement	Ability to make rapid arm movements where accuracy is not required, such as gathering trash or debris and throwing it into a large pile.

Table 3 (Continued)

Title	Description
Skill Descriptions	
Psychomotor (Con t.):	
6. Rate control	Ability to make continuous equipment adjustments relative to a moving target changing in speed and direction, such as following a bird with a rifle, or tracking a target across a CRT display using a trackball or light pen.
7. Manual dexterity	Ability to make skillful arm and hand movements in handling rather large objects under speeded conditions, such as assembling or disassembling a military rifle.
8. Finger dexterity	Ability to make skillful manipulations of small objects with the fingers, such as sorting out an assortment of objects, or making nut-and-bolt connections.
9. Arm-hand steadiness	Ability to make precise arm-hand positioning movements that do not require strength or speed, such as routine soldering of wires, or replacement of delicate equipment components or subassemblies.
10. Wrist-finger speed	Ability to make rapid tapping movements with the wrist and fingers, such as transmitting Morse Code with a telegraphic key, or tapping equipment components with a small hammer to assure secure positioning.
11. Aiming	Ability to activate small equipment elements quickly, repeatedly, and accurately, such as data entry keyboards, test point probes, or communication channel switches.

3. The engineers were then asked to take the top card from their skill decks and place it in the top center bin of a sorting board. The particular skill title--and definition--on that card was the skill to be applied throughout the first sort. The next five cards in the deck carried skill level indicators; these were placed in the center row of the sorting board in sequence from left to right (level #1 on the extreme left bin, level #2 next, etc. as shown in Figure 1). The five skill level cards represented a 5-point Likert scale, as defined below:

Skill level 1: The task does not require this skill at all.

Skill level 2: The task requires a small amount of this skill.

Skill level 3: The task requires a moderate amount of this skill.

Skill level 4: The task requires a high degree of this skill.

Skill level 5: The task requires a maximum amount of this skill.

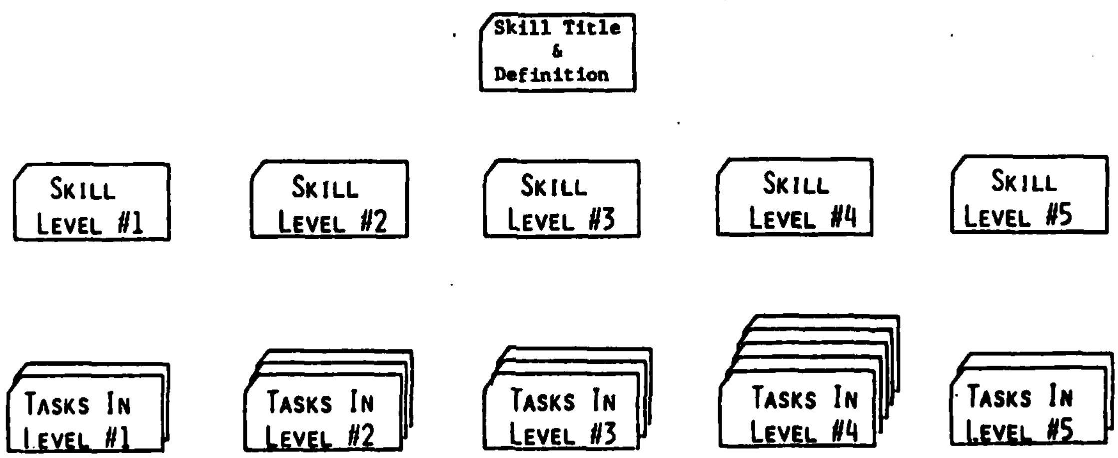

Figure 1. Structured survey: Card sorting procedure.

4. The remaining cards in the first card deck were the task titles and descriptions shown in Table 3. Taking each task card in succession, the subject read it, noted the skill title and definition in the top center bin, and estimated the level of skill (1 through 5) required to perform that task. The task card was then placed in the appropriate bin in the bottom row of the sorting board, just below the skill level card carrying the number of the estimated skill level.

5. The engineer then continued through the package of task cards, sorting them as in step 4. When one package of task titles was completed, the experimenter picked up the cards and the subject proceeded to the next package of cards (i.e., a second skill title with definition and the 15 operation and 14 maintenance tasks).

RESULTS AND DISCUSSION

Responses to the Unstructured Survey

Since engineers were not given a formal framework for reporting the tasks and skills in the unstructured survey, it was impossible to pool calculations across subjects. Some observations were made:

1. The 96 different action or key words used by the subjects to describe the tasks and skills required in system operation and maintenance are listed in alphabetical order in Table 4. In a few cases, the same word was termed both a task and a skill required for both operation and maintenance. In other cases, the same word appeared in two or three categories. Most listings were generated in only one of the four categories.

Table 4

Task and Skill Keywords Used by Engineers

	Operator Tasks	Maintenance Tasks	Operator Skills	Maintenance Skills
1	—	—	Ability	Ability
2	Adjust	Adjust	—	—
3	Alert	—	—	—
4	Align	Align	—	—
5	Analyze	Analyze	—	Analyze
6	—	—	—	Aptitude
7	—	Assemble	—	—
8	Assign	—	—	—
9	—	—	Association	—
10	—	Bring up	—	—
11	—	—	Capability	—
12	Catalog	—	—	—
13	Check	Check	—	—
14	Classify	—	—	—
15	—	Clean	—	—
16	Communicate	—	—	—
17	—	Compare	Compare	—
18	—	—	Concentrate	—
19	Conduct	—	—	—
20	Control	—	—	—
21	Coordinate	—	Coordinate	—
22	—	Correct	—	—
23	—	—	Correlate	—
24	Decide	—	—	—
25	—	—	—	Deduce
26	Designate	—	—	—
27	—	—	—	Desire
28	Detect	—	Detect	—
29	—	Determine	—	—
30	—	—	Dexterity	Dexterity
31	Discriminate	—	Discriminate	—
32	Edit	—	—	—
33	Enter Data	—	—	—
34	Evaluate	Evaluate	Evaluate	Evaluate
35	—	—	Experience	—
36	Extract	—	Extract	—
37	Eye-hand Coord.	—	Eye-hand Coord.	—
38	—	—	Familiarity	Familiarity
39	Follow Instructions	Follow Instructions	Follow Instructions	Follow Instructions
40	—	—	Gather Information	Gather Information
41	Handle	—	—	—
42	Identify	Identify	Identify	—
43	Initialize	Initialize	—	—
44	—	Install	—	—
45	Interpret	Interpret	Interpret	Interpret
46	—	—	—	Intuition
47	—	Isolate	—	—

Table 4 (Continued)

	Operator Tasks	Maintenance Tasks	Operator Skills	Maintenance Skills
48	—	—	Judgment	—
49	Knowledge	—	Knowledge	Knowledge
50	Localize	Localize	—	—
51	—	Lubricate	—	—
52	—	—	Manipulate	Manipulate
53	—	—	Memory	Memory
54	—	—	—	Measure
55	Monitor	Monitor	—	—
56	—	—	—	Motor Skills
57	Observe	Observe	—	—
58	—	Obtain (Retrieve)	—	—
59	—	Operate	Operate	Operate
60	—	—	Perception	—
61	Perform	Perform	—	—
62	—	—	—	Practice
63	Prepare	—	—	—
64	—	—	—	Problem Solve
65	Program	—	Program	—
66	React	—	—	—
67	—	Read	Read	Read
68	—	—	—	Reasoning
69	Recognize	Recognize	Recognize	Recognize
70	—	—	Relate	—
71	—	Remove	—	Remove
72	—	Repair	—	Repair
73	—	Replace	—	Replace
74	Report	Report	—	—
75	—	—	Respond	—
76	—	Restore	—	—
77	—	Run	—	—
78	Search	—	—	—
79	Select	Select	Select	—
80	Set up	Set up	—	—
81	—	—	—	Solder
82	—	—	Spatial Relations	—
83	Supervise	—	—	—
84	Test	Test	—	—
85	—	—	—	Trace Signals
86	Track	—	Track	—
87	Troubleshoot	Troubleshoot	—	Troubleshoot
88	—	Tune	—	—
89	—	—	Type	Type
90	—	—	Understand	—
91	—	—	Use	Use
92	—	Verify	—	—
93	—	—	Vision	—
94	—	—	—	Visual Activity
95	—	—	Visual Discrim.	—
96	—	—	Visualization	Visualization

2. Despite the variety of terms generated, few tasks and skills were listed. The number of tasks ranged from 4 to 10, with a median of 7, and skills ranged from 2 to 16, with a median of 5. When the skill level estimates were subjected to factor analysis, the distribution of factors was:

Number of Factors	Frequency (Engineers)
4	2
3	8
2	16 (median)
1	4
0	10

Thus, engineers' unstructured responses revealed a lack of standardized vocabulary for describing tasks and skills, and relatively simplistic (few-factor) concepts of operation and maintenance in Navy electronic systems.

These results, while not completely unexpected, are somewhat distressing. To make manpower trade-offs among alternative design concepts, engineers must analyze their designs in terms of the tasks to be performed by each alternative, the skills these tasks demand, and, in particular, the levels of those skills. If they lack the capacities to perform such analyses, they cannot select the design configuration requiring the least skill. It is, however, not surprising that they lack these capabilities, because they have not been trained to apply behavioral concept structures to their work. Possibly, if they were given such concept structures, they would exhibit greater fluency in performing task/skill analyses.

Responses to the Structured Task/Skill Survey

When provided with the structured sets of 14 maintenance tasks, 15 operation tasks, and 22 skills, the judgments were more precise and concepts of operation and maintenance were composed of more factors than from the unstructured survey.

Engineers were able to differentiate the various tasks in terms of a 5-point scale of skill level, which they were incapable of doing in the unstructured survey. This suggests that engineers are able to conceptualize skill level, but that they lack a language or framework for expressing these concepts.

For example, they were able to rank the various operation and maintenance tasks in terms of the types and levels of skills demanded by these two task categories (Table 5). It is interesting to note that the absolute level of skill required by maintenance tasks is considered to be somewhat higher than that required by operations tasks. The ranking of the individual skills per task type also varied, suggesting that to the engineers the two types of tasks demand somewhat different patterns of skills.

Table 5

Skill Requirements as Ranked by Engineers
for Two Groups of Tasks

Rank	Operation Task[a]	Rank	Maintenance Task[b]
1	Rote memory	1	Verbal comprehension
2	Visual speed	2	Rote memory
3	Deductive reasoning	3	Finger dexterity
4	Idea formation	4	Multilimb coordination
5	Verbal comprehension	5	Manual dexterity
6	Reaction time	6	Arm-hand steadiness
7	Aiming	7	Control precision
8	Response orientation	8	Deductive reasoning
9	Pattern sensitivity	9	Visual speed
10	Spatial visualization	10	Aiming
11	Span memory	11	Pattern sensitivity
12	Spatial orientation	12	Idea formation
13	Finger dexterity	13	Spatial visualization
14	Number facility	14	Spatial orientation
15	Multilimb coordination	15	Span memory
16	Fluency	16	Response orientation
17	Control precision	17	Rate control
18	Arm-hand steadiness	18	Number facility
19	Wrist-finger speed	19	Fluency
20	Rate control	20	Reaction time
21	Manual dexterity	21	Speed-of-arm movement
22	Speed-of-arm movement	22	Wrist-finger speed

[a]Range of mean ratings on 5-point scale: 2.88 to 1.47.

[b]Range of mean ratings on 5-point scale: 3.14 to 1.84.

Table 6 ranks operation tasks by difficulty and maintenance tasks in terms of engineers' judgments of the level of skill required for task performance. This table suggests that engineers can more readily differentiate the skill level requirements for individual maintenance tasks than for the individual operating tasks. The maintenance task rankings appear to be more logical than the corresponding rankings of operating tasks. For example, it is difficult to see why much more skill is required to operate discrete control devices (3rd) than to interpret visual and auditory data (11th). This may also indicate that engineers consider equipment operation a much more homogeneous activity--and, therefore, more difficult to fractionate--than maintenance. The implication one might draw from this is that engineers would find it easier to analyze their design configurations in terms of maintenance skill level relationships than for operating tasks.

Inasmuch as the engineers responded to the structured survey in terms of the 22 basic skills, the results were combined and a single factor rotation was performed for the entire body of data. The results were four significant factors for maintenance skills as conceptualized by our sample, and three significant factors for the operation skills. Twelve of the component skills were considered appropriate to the maintenance tasks; and 11 to the operation task. The cognitive skills--such as idea formation, deductive reasoning, and number facility--tended to appear only under the maintenance designation, whereas the psychomotor skills--such as manual dexterity and arm-hand steadiness--were common to both. It would seem that the engineers in the sample conceive of maintenance as a more demanding--indeed, more skillful--process than operation.

Table 6

Task Difficulty Ranked by Engineers

Rank	Task
Operation	
1	Perform correct sequence of operating procedures
2	Supply or enter data to implement decisions
3	Operate discrete control devices
4	Select appropriate course of action
5	Receive/transmit communications relevant to operation
6	Perform preventive maintenance
7	Operate continuous control devices
8	Observe and interpret visual displays and indicators
9	Establish desired operating modes
10	Monitor equipment operation
11	Interpret visual and auditory data to assist in decision making
12	Initiate equipment operation
13	Perform quantitative computations
14	Read and understand text
15	Recognize and interpret auditory signals
Maintenance	
1	Perform in-place adaptive corrections
2	Isolate malfunctions to identifiable unit
3	Verify satisfactory functioning of replacement unit/component
4	Verify failure or malfunction
5	Restore equipment/system to operational condition
6	Operate BITE, and/or connect and operate support or test equipment
7	Replace malfunctioning unit/component
8	Remove malfunctioning unit/component
9	Set initial conditions required for maintenance
10	Perform preventive maintenance
11	Select and use tools necessary for maintenance
12	Inspect equipment
13	Obtain physical access to equipment
14	Perform corrosion control procedures

Note: For operation tasks, the range of mean ratings on a 5-point scale is 2.45 to 1.62; for maintenance tasks, the range is 2.83 to 1.65.

Table 7 shows the four dimensions of skill generated by the sample for maintenance, and the three dimensions generated for operation. Only two of these were unitary: Factor IV (reaction time) for maintenance and Factor III (fluency) for operation. Only those components having factor loadings greater than the square root of 2 are shown, which accounts for at least half the item variance.

Table 7

Skill Factor Groupings from Structured Survey

Maintenance Skill	Operation Skill
Factor I	Factor I
Pattern sensitivity	Control precision
Idea formation	Multilimb coordination
Span memory	Manual dexterity
Number facility	Finger dexterity
Visual speed	Arm-hand steadiness
Deductive reasoning	Wrist-finger speed
	Aiming
Factor II	Factor II
Manual dexterity	Pattern sensitivity
Finger dexterity	Spatial orientation
Arm-hand steadiness	Spatial visualization
Factor III	Factor III
Spatial orientation	Fluency
Speed-of-arm movement	
Factor IV	
Reaction time	

Note: Skill groupings from factor analysis. Only those skills are shown for which the associated factor accounted for more than half the variance (loading in excess of $\sqrt{2}$).

The fact that 6 of the 12 appropriate maintenance skills and 7 of the 11 appropriate operation skills, respectively, are grouped under a single factor indicates that these concepts are neither well attended to nor well differentiated by the engineers in the sample. This conclusion is also supported by the small number of factors generated for the original list of 22 orthogonal skill components.

CONCLUSIONS

1. Engineers have relatively few and nondifferentiated concepts of operation and maintenance skills. Their responses to self-generated lists of tasks and skills produced a median of two factors or skill sets.

2. They consider that the skills required for operating and maintenance tasks differ significantly. Equipment maintenance is more difficult, requiring a higher skill level that is oriented primarily on cognitive capabilities, whereas operating tasks are oriented around psychomotor abilities.

3. It is possible to increase the sophistication of the engineers' skill concepts by providing them with a structured situation that leads them through the skill analysis process. Their responses to prescribed lists of tasks and skills produced a median of five factors (compared with the two factors produced by the unstructured survey).

The implications of these findings are both distressing and hopeful. Anyone who expects engineers on their own to make design trade-offs involving skill will be distressed by the results. It is unlikely that, without being pressed contractually, engineers will pursue such analyses; even if they were to do so, the products of these analyses would have limited usefulness.

On the other hand, it is a hopeful sign that the engineers can improve their analytic capabilities by following procedures established by behavioral scientists. Since it is impossible to provide a personal human factors specialist for each design engineer, a surrogate must be provided. This can be some sort of design guide that provides a sample procedure with the data necessary for implementation.

RECOMMENDATIONS

A personnel design requirements handbook should be developed to enable hardware designers to assess the personnel implications of hardware system design concepts.

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APPENDIX

TEST/SURVEY BATTERY INSTRUMENTS

This appendix contains copies of materials and instructions used in the test/survey battery administered to 40 engineer subjects participating in the study. The completed test/survey battery and other data are at NAVPERSRANDCEN.

EFFECT OF EQUIPMENT DESIGN CHARACTERISTICS
ON USER SKILL-LEVEL REQUIREMENTS

GENERAL INFORMATION

We are asking you and a number of engineers to take part in a study aimed at improving the ways in which developers of military systems give consideration to manpower problems early in system design. Although the study is funded by the Navy, it addresses a problem which is common to all U.S. services: the complexity and sophistication of military electronic systems appears to be outrunning the supply of persons who are able (even after training) to operate and maintain them.

The particular part of this problem we are studying has to do with the differences in skill level that might be required of Navy crew persons as a result of differences in equipment items chosen by an engineer when he first designs an electronic system. Ultimately, the Navy is seeking an effective way to help engineers take the skill-level problem into account when these early design decisions are being made. Any such "effective way" will have to begin with engineers like yourself, and with information indicating how you perceive this problem and how you make design decisions.

The long-range objective of this and related studies is to discover how various design characteristics may impact the skill levels required of personnel who operate and maintain the resulting equipment. To achieve the objective of our specific study, we have several survey-type booklets and procedures we would like you to complete. Some concentrate on tasks performed by military personnel, and the skills that are necessary for accomplishing those tasks. Another will examine the way you can visualize a simple form when it is hidden within a complex pattern, and still another will ask how you usually regard certain management/social/individual situations.

With the exception of the design puzzle booklet, there are no "right" or "wrong" answers to any of the survey items you will encounter. We need your thoughtful responses to the survey items solely in terms of your engineering experience to date, and your present knowledge and feelings.

After we have completed our analysis of the response data you will be informed of the results. Our plan is to summarize the group data without identifying individuals by name, but to indicate to each of you separately the location of his or her responses with respect to the grouped data.

RESPONDENT'S BIOGRAPHICAL DATA

Your Name .... Your Age ....

Undergraduate Education:

Years Completed........ Major Field ....

Graduate Education:

Years Completed........ Major Field ....

Years of Design Experience........ % in Management/Supervisory Role.......

Name of Most Recent System Worked On ....

Nature of Your Design Work on the System ....

Have You Worked on Similar Systems in the Past?

<u>Name of System</u>	<u>Nature of Design Work</u>

Unstructured Survey

ESTIMATES OF SKILL LEVELS REQUIRED BY OPERATOR TASKS

This survey is part of a study attempting to identify the influence exerted on a system's engineering design by the designer's perception of the skills of the persons who will operate the system.

On these pages you will be asked:

- to generate a list of tasks associated with operating the designated type of equipment,
- to determine some of the skills that are important in operating that equipment, and
- to indicate the level of each skill you regard as necessary for successful performance of each listed task.

The following pages have been designed to provide a framework in which you can make your responses conveniently. A separate page will be provided at the conclusion of this session. Make any comments you wish that will improve this survey form itself, because it may be used with other engineers in the future.

Assume that you are part of an engineering design team, and that you are currently involved in design decisions regarding

____

(Enter system or equipment identification.)

Think of this particular subdivision of system equipment in terms of your design experience, and consider the most important tasks that will have to be performed by military or civilian personnel in field operation of the equipment.

Make a list of these tasks in the spaces below. Please indicate a minimum of 4 tasks; try to generate as large a number of tasks as possible. Develop your list of tasks by giving thought to the equipment in normal and degraded modes, and in the variety of environments the system would typically encounter in peacetime and wartime circumstances.

TASK LIST

1 ....

2 ....

3 ....

4 ....

5 ....

6 ....

7 ....

8 ....

When you have finished your listing, tell your interviewer how many tasks you have listed; he will provide you with the next page of this survey.

Place this page beside the one on which you wrote your list of tasks so that you can easily look from one page to the other and back again. The triads of numbers down the left margin are selected combinations of tasks from the listing you generated on the preceeding page.

In responding to the first line below, look in your list at the three tasks corresponding to the set of three numbers shown. Considering these three tasks only, think of a skill that is required by any two of the tasks but not required (or required to a far lesser degree) by the third task. You are looking for a skill that a military or civilian operator or technician must have for performing any two of these tasks, but needs only a minimum amount or none of that skill for the remaining task.

On the first line below, write a name or a brief descriptive phrase for the skill you have determined to be required for two of the three specified tasks. Proceed to the second line and make a similar judgment regarding the three tasks specified there. Continue until you have written a response opposite each set of three numbers.

TASK NUMBER FROM YOUR LIST	Name of Skill Required by Any Two of the Tasks
2,3,4	
1,2,3	
3,4,5	
1,2,5	
1,4,5	

When you have finished these judgments, give both pages of your listings to your interviewer.

<u>Note</u>: **The triads were specified if respondent had generated 5 tasks on preceding page.**

The left margin of this page (and all others in this portion of the survey) carries the list of tasks you generated on page 2. At the top of the right margin you will find one of the key skills you listed on page 3. In the response space below, estimate the degree to which each task in the list demands the particular skill written in the upper right corner of the response space, and write a number for that degree in the box provided. Use the following scale to select the numbers you enter in the boxes:

1 -- does not require this skill at all

2 -- requires a small amount of this skill

3 -- requires a moderate amount of this skill

4 -- requires a high degree of this skill

5 -- requires a maximum amount of this skill

SKILL:

TASK LIST

1 .... ☐

2 .... ☐

3 .... ☐

4 .... ☐

5 .... ☐

6 .... ☐

7 .... ☐

8 .... ☐

9 .... ☐

10 .... ☐

11 .... ☐

12 .... ☐

13 .... ☐

14 .... ☐

15 .... ☐

When you have entered a skill-level estimate in each of the boxes corresponding to a task, proceed to the next page. It will contain a reprint of the instructions and the task list, but a different skill will be written in the upper right corner of the response space. The judgments required of you are the same as those you have just completed on this page.

Unstructured Survey

ESTIMATES OF SKILL LEVELS REQUIRED BY MAINTENANCE TASKS

This survey is part of a study attempting to identify the influence exerted on a system's engineering design by the designer's perception of the skills of the persons who will maintain the system.

On these pages you will be asked:

- to generate a list of tasks associated with maintaining the designated type of equipment,
- to determine some of the skills that are important in maintaining that equipment, and
- to indicate the level of each skill you regard as necessary for successful performance of each listed task.

The following pages have been designed to provide a framework in which you can make your responses conveniently. A separate page will be provided at the conclusion of this session. Make any comments you wish that will improve this survey form itself, because it may be used with other engineers in the future.

Assume that you are part of an engineering design team, and that you are currently involved in design decisions regarding

---

(Enter system or equipment indentification)

Think of this particular subdivision of system equipment in terms of your design experience, and consider the most important tasks that will have to be performed by military or civilian personnel in field maintenance of the equipment.

Make a list of these tasks in the spaces below. Please indicate a minimum of 4 tasks; try to generate as large a number of tasks as possible. Develop your list of tasks by giving thought to the equipment in normal and degraded modes, and in the variety of environments the system would typically encounter in peacetime and wartime circumstances.

TASK LIST

1 ....

2 ....

3 ....

4 ....

5 ....

6 ....

7 ....

8 ....

When you have finished your listing, tell your interviewer how many tasks you have listed; he will provide you with the next page of this survey.

Place this page beside the one on which you wrote your list of tasks so that you can easily look from one page to the other and back again. The triads of numbers down the left margin are selected combinations of tasks from the listing you generated on the preceeding page.

In responding to the first line below, look in your list at the three tasks corresponding to the set of three numbers shown. Considering these three tasks only, think of a skill that is required by any two of the tasks but not required (or required to a far lesser degree) by the third task. You are looking for a skill that a military or civilian operator or technician must have for performing any two of these tasks, but needs only a minimum amount or none of that skill for the remaining task.

On the first line below, write a name or a brief descriptive phrase for the skill you have determined to be required for two of the three specified tasks. Proceed to the second line and make a similar judgment regarding the three tasks specified there. Continue until you have written a response opposite each set of three numbers.

TASK NUMBER FROM YOUR LIST	Name of Skill Required by Any Two of the Tasks	
2,3,4	....	☐
5,6,7	....	☐
1,6,7	....	☐
1,3,6	....	☐
1,3,4	....	☐
2,4,5	....	☐
2,5,7	....	☐
1,2,7	....	☐
3,5,7	....	☐
3,4,6	....	☐
1,4,5	....	☐
2,3,7	....	☐
1,2,6	....	☐
4,5,6	....	☐
	....	☐
	....	☐
	....	☐
	....	☐
	....	☐
	....	☐

When you have finished these judgments, give both pages of your listings to your interviewer.

Note: These triads were specified if respondent had generated 7 tasks for list on preceding page.

The left margin of this page (and all others in this portion of the survey) carries the list of tasks you generated on page 2. At the top of the right margin you will find one of the key skills you listed on page 3. In the response space below, estimate the degree to which each task in the list demands the particular skill written in the upper right corner of the response space, and write a number for that degree in the box provided. Use the following scale to select the numbers you enter in the boxes:

1 -- does not require this skill at all

2 -- requires a small amount of this skill

3 -- requires a moderate amount of this skill

4 -- requires a high degree of this skill

5 -- requires a maximum amount of this skill

SKILL:

TASK LIST

1 .... ☐

2 .... ☐

3 .... ☐

4 .... ☐

5 .... ☐

6 .... ☐

7 .... ☐

8 .... ☐

9 .... ☐

10 .... ☐

11 .... ☐

12 .... ☐

13 .... ☐

14 .... ☐

15 .... ☐

When you have entered a skill-level estimate in each of the boxes corresponding to a task, proceed to the next page. It will contain a reprint of the instructions and the task list, but a different skill will be written in the upper right corner of the response space. The judgments required of you are the same as those you have just completed on this page.

STRUCTURED SURVEY

Instructions for Structured Survey of Skill Level Estimates

This is a sample set of cards similar to those you will be working with for the next part of this study. Read through them quickly, just to get an idea of their content. In making the estimates we will ask of you, you will always have the required tasks and skills before you in this printed form.

(Allow time for subject(s) to read through cards)

Each package/section of cards in this survey contains a complete set of the task titles and descriptions you have just read. In addition, the first card carries one of the skill titles/descriptions we have developed, and also five cards comprising a rating scale for your estimates of skill level. You will make your responses by sorting the task cards into categories, using a sorting board.

From the top of your card deck, place the first card in the top center bin on the sorting board. It carries a particular skill title and definition, and is the skill we want you to use throughout your first sort. The next five cards carry skill-level indicators; place them in the center row on the sorting board in sequence from left to right (level #1 in the extreme left bin, level #2 next, and so on until level #5 is in the extreme right bin).

The remaining cards in your first package are a collection of task titles and descriptions. Taking each task card in succession, read its task title and description, note again the skill title and definition in the top center bin, and estimate what level of skill (from 1 to 5) is required in performance of the task shown on the card you are reading. Place the card in the appropriate bin on the bottom row of the sorting board, just below the skill level card carrying the number of your skill-level estimates. Continue through the package of task cards, sorting them according to your best judgement among the five bins representing skill-level estimates. When you have finished one package, have your interviewer pick up the cards. When the sorting board is cleared, take the next package of cards from your deck and repeat the sorting process. Continue until you have categorized all the packages contained in the deck.

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